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Cryogenic Fluid Management Technology Workshop
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LARGE CAPACITY CRYOPROPELLANT ORBITAL STORAGE FACILITY

Under contract to the Marshall Space Flight Center a comprehensive study was performed to develop the major features of a large-capacity, orbital propellant storage facility for the space-based, cryogenic Orbital Transfer Vehicle (OTV). Projected propellant usage and delivery schedules can be accommodated by two orbital tank sets of 100,000 lb storage capacity, with advanced missions expected to require increased capacity. This cryogen depot will require new technologies for fluid management in microgravity and further development of thermal management technologies for minimization of cryogen boiloff. These technologies include liquid acquisition devices, tank pressurization methods, a thermodynamic venting system, thick multilayer insulation, vapor-cooled shields, low-conductance structural supports and penetrations, long-lived solar-selective coatings, possibly refrigeration systems, and micrometeoroid/debris protection.

Preliminary evaluations have been made to define a test program approach for reducing technical risk through verifying performance models and building a base of engineering data for depot design. A number of testing options were defined and evaluated, leading to selection of ground testing combined with an orbital systems test. The orbital test could either be a short-term test carried out in the cargo bay of the Space Shuttle Orbiter using a non-hazardous cryogen or a longer-term test carried out with hydrogen aboard a free-flying experiment orbited with an expendable launch vehicle.

GENERAL DYNAMICS
Space Systems Division

LONG TERM CRYOGENIC STORAGE FACILITY SYSTEMS STUDY

The Long Term Cryogenic Storage Facility (LTCSF) Systems Study has five principal objectives.

1) Definition of preliminary concept designs for four storage facility concepts;

2) Selection of preferred concept(s) through the application of trade studies to candidate propellant management system components;

3) Preparation of a conceptual design for an orbital storage facility;

4) Development of a test program to demonstrate facility performance; and

5) Development of a technology plan.

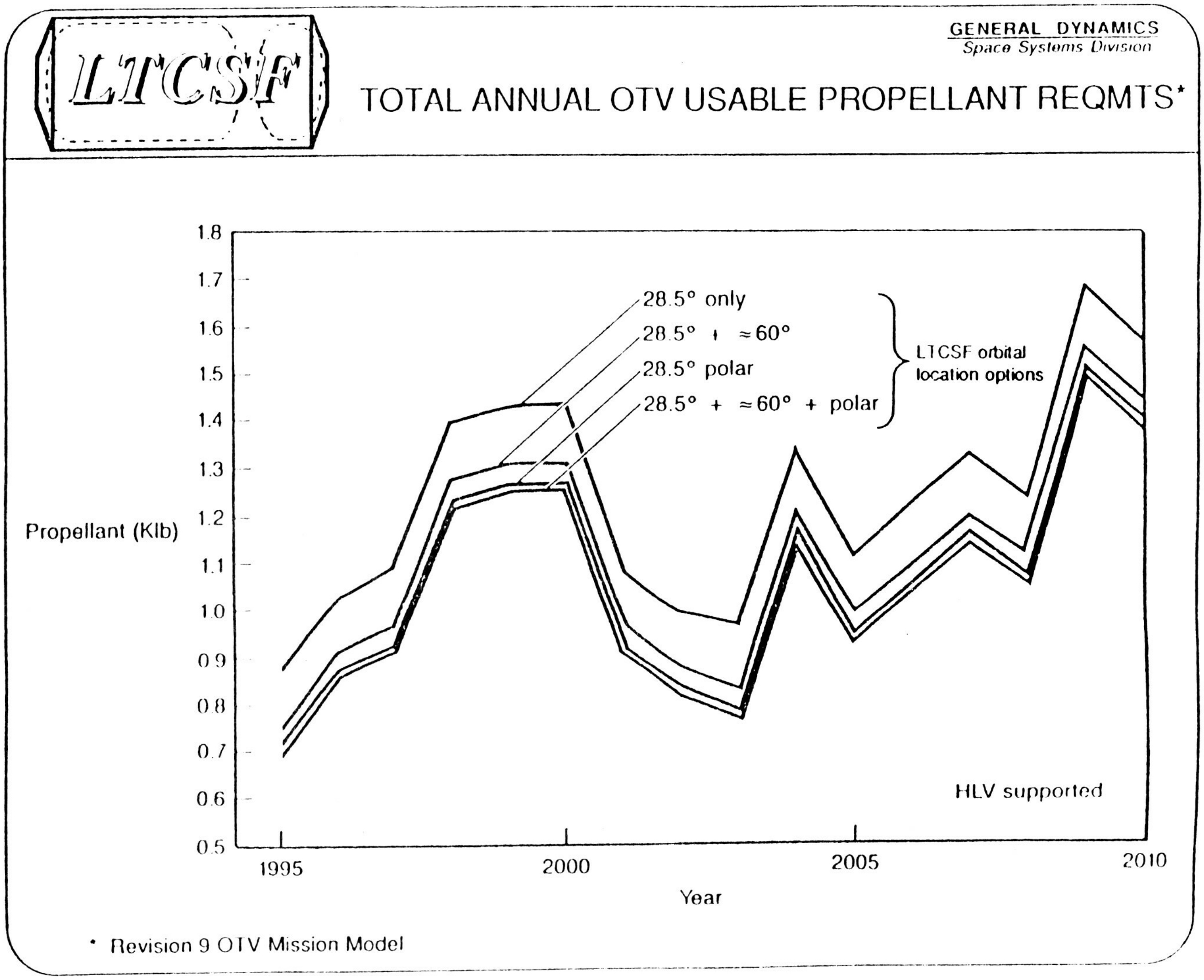
LONG TERM CRYOGENIC STORAGE FACILITY SYSTEMS STUDY (OTV CRYOPROPELLANT DEPOT)

OBJECTIVES:

- DEFINITION OF PRELIMINARY CONCEPT DESIGNS
  - STORAGE UTILIZING PASSIVE CONTROL ONLY
  - STORAGE UTILIZING REFRIGERATION SYSTEMS
  - STORAGE UTILIZING PARTIAL RELIQUEFACTION SYSTEMS
  - STORAGE UTILIZING TOTAL RELIQUEFACTION SYSTEMS (NON VENTING)
- SELECTION OF PREFERRED CONCEPT(S) VIA TRADE STUDIES
- CONCEPTUAL DESIGN OF ORBITAL STORAGE FACILITY
- DEVELOPMENT OF A TEST PLAN
- DEVELOPMENT OF A TECHNOLOGY PLAN

TOTAL ANNUAL OTV USABLE PROPELLANT REQUIREMENTS

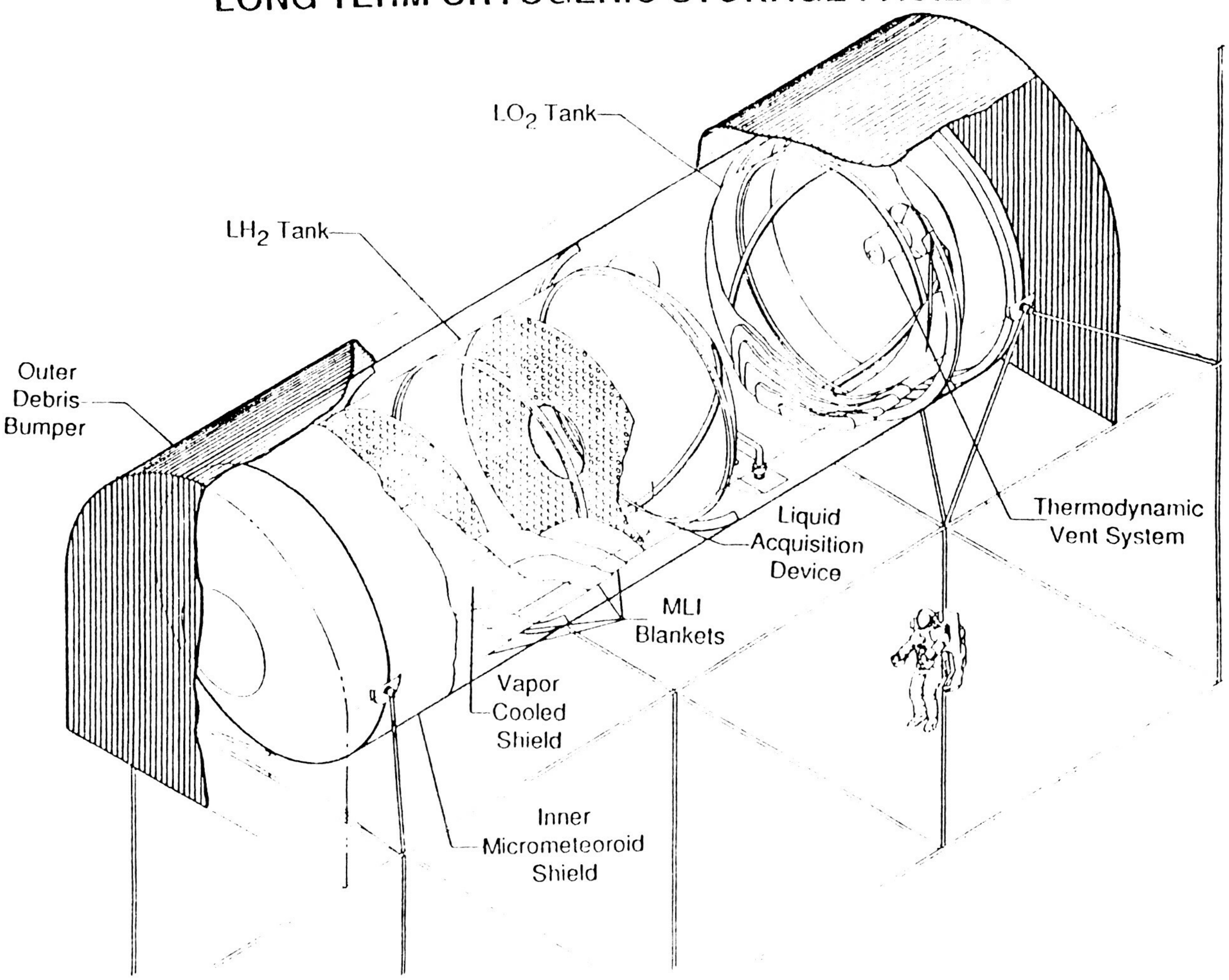
This chart shows the propellant requirements required to meet the NASA/MSFC rev. 9 OTV mission model if single or multiple propellant depots are deployed at various inclinations around the earth. Multiple depots would reduce propellant requirements.



LONG TERM CRYOGENIC STORAGE FACILITY

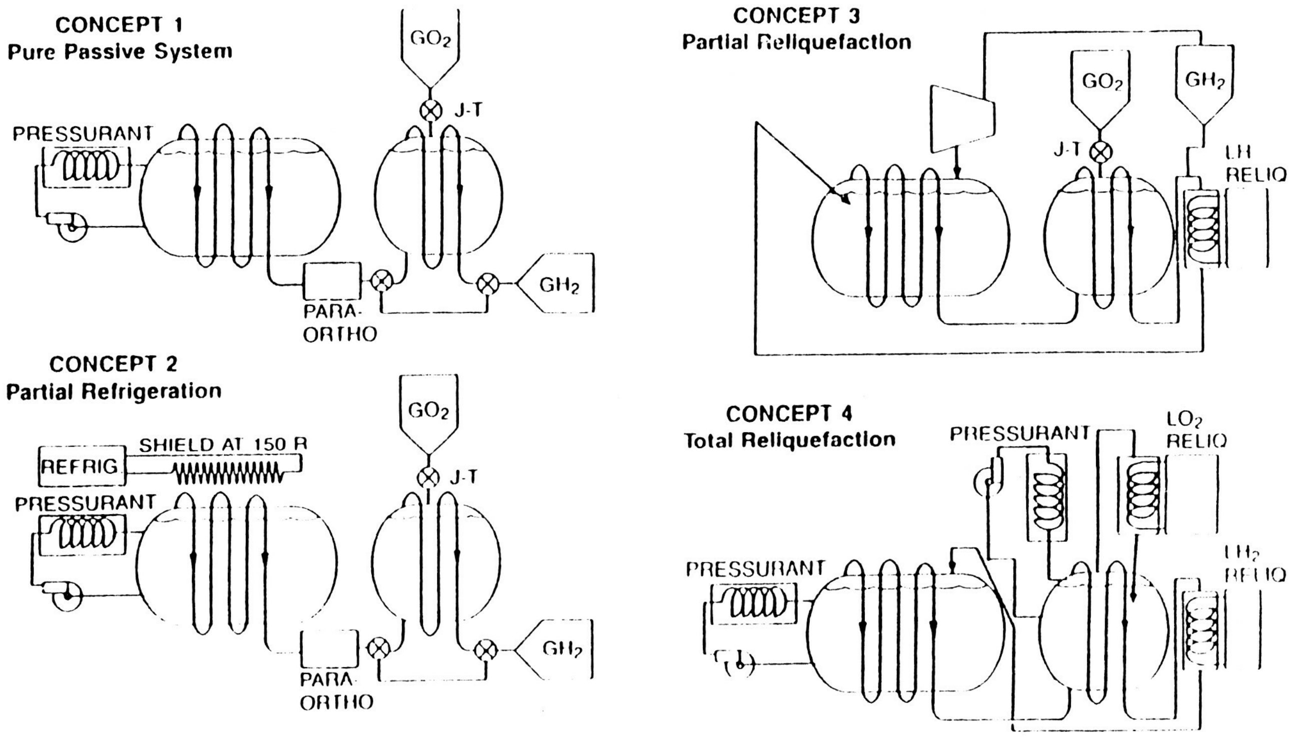
The OTV annual propellant requirement can be met by providing 200,000 lb of on-orbit propellant storage capacity, assuming a resupply frequency of ninety days or longer. The storage capacity is provided by two tank sets containing both a hydrogen and oxygen tank with features to permit zero-g operation, limit environmental heating and provide protection against micrometeoroids and debris.

LONG TERM CRYOGENIC STORAGE FACILITY



The four propellant storage concepts are very similar: all route hydrogen boiloff through vapor-cooled shields (VCSs) on the hydrogen and oxygen tanks. Concepts 1, 2 and 3 store both hydrogen and oxygen boiloff in high pressure accumulators whereas Concept 4 reliquefies all boiloff and returns it to the tanks. Concept 2 has an additional shield that is connected to a refrigerator. Concepts 1, 2 and 3 use high pressure accumulated oxygen boiloff for oxygen tank autogenous pressurization during OTV tanking. Concept 4 uses a liquid pump and heat exchanger to provide autogenous oxygen pressurization. Concept 3 is the only concept using high pressure accumulated hydrogen for hydrogen tank autogenous pressurization. The other concepts use a pump and heat exchanger.

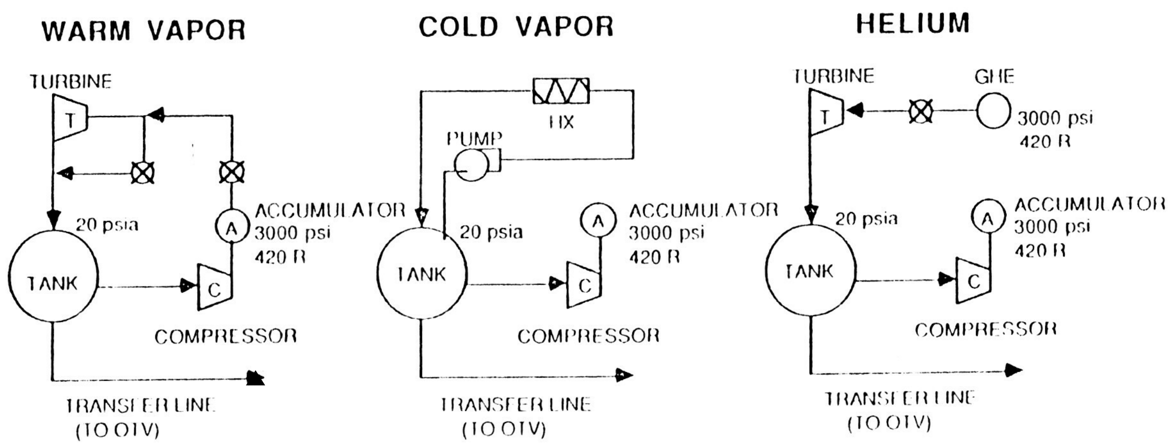
CONCEPT SCHEMATICS



TANK PRESSURIZATION SCHEMES

Three basic tank pressurization methods were considered for carrying out fluid transfer. Vaporization of liquid is preferred in most cases for hydrogen and use of accumulated boiloff expanded through a turbine or J-T valve is preferred in most cases for oxygen. High pressure helium gas was also considered, but it is the least attractive due to problems which arise during subsequent no-vent refill operations.

TANK PRESSURIZATION SCHEMES

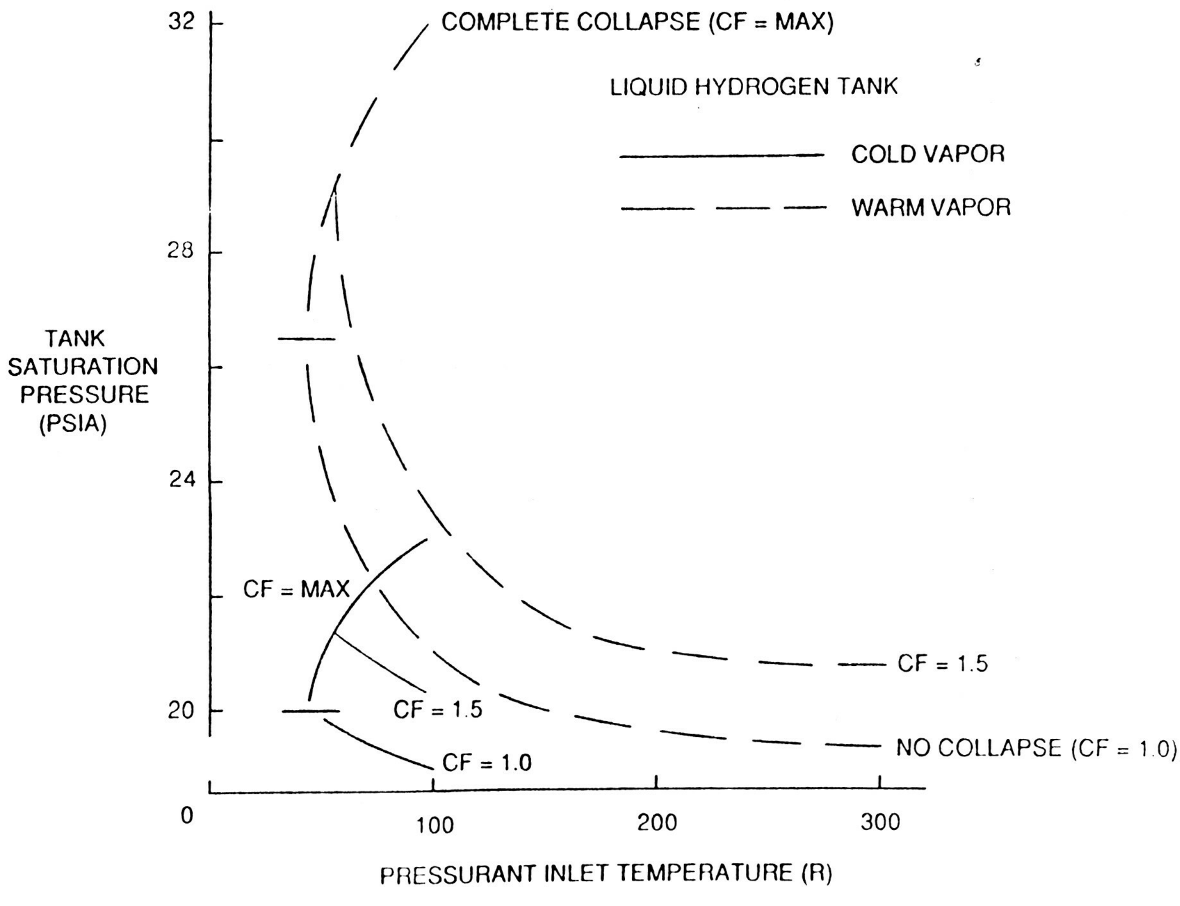


- USES WARM BOILOFF ACCUMULATED AT HIGH PRESSURE AND EXPANDED THROUGH TURBINE
- USES PRESSURIZED COLD LIQUID VAPORIZED IN HEAT EXCHANGER
- USES STORED HIGH PRESSURE HELIUM GAS EXPANDED THROUGH TURBINE

TANK SATURATION PRESSURE AT COMPLETION OF POST-TRANSFER MIX

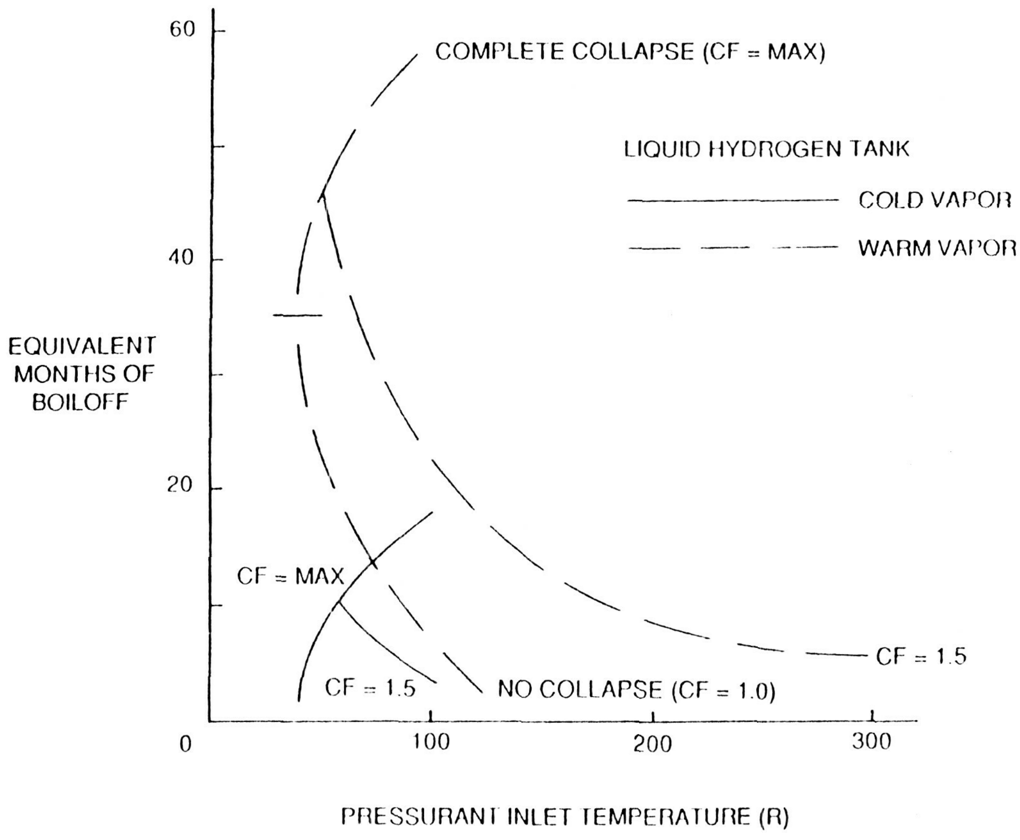
When relatively warm pressurant vapor is injected into a cryogenic propellant tank, its temperature drops as heat and mass transfer occur. The ratio of actual pressurant quantity to the quantity which would be required if no heat or mass transfer were to occur in the ullage has been called the "collapse factor." The greater the collapse factor the more the pressurant that must be injected to maintain a given tank pressure. "Complete collapse" means that the pressurant temperature falls to the liquid saturation temperature during transfer, the worst case situation requiring the most pressurant. These factors are fairly well known for typical vehicle outflow conditions where the propellants are settled. For a cryogenic propellant storage depot operating in the microgravity environment of space, collapse factors are more difficult to estimate. After the depot tank contents are mixed at the completion of transfer, the equilibrium saturation condition is a strong function of both the type ("cold vapor" or "warm vapor") of pressurant and the degree of pressurant collapse. Injecting warm vapor from the boiloff accumulator to pressurize the tank causes a substantial increase in mixed saturation pressure due to the much higher vapor stored energy and to the presence of the para/ortho heat of conversion. If pressurant collapse is too high, increased thermodynamic vent system operation will be required to return the tank to the nominal thermodynamic condition.

TANK SATURATION PRESSURE AT COMPLETION OF POST-TRANSFER MIX



If the saturation pressure at the completion of post-transfer mix is greater than the nominal value prior to transfer, the tank fluid must be returned to its initial thermodynamic condition. One method of achieving this involves operating the thermodynamic vent system at an increased level, throttling the vented fluid to a low pressure, and then using the fluid as a heat sink to cool the tank contents. This chart shows the boiloff penalty required to return the tank fluid to its nominal condition in terms of equivalent months of steady state boiloff. For the liquid hydrogen tank, warm vapor pressurization is seen to be costly. Even for the cold vapor system, every effort must be made to minimize the pressurant collapse factor to avoid injecting an excessive amount of energy into the closed tank.

PRESSURIZATION BOILOFF PENALTY



LTCSF PROPELLANT TRANSFER CONFIGURATIONS

For propellant transfer from the storage depot to the OTV, three transfer configurations were considered: pressure-fed, pump-assisted, and pump-fed. The pump-assisted configuration consists of pumped transfer with sufficient pressurant injection to subcool the storage tank liquid during the transfer operation. No pressurant is injected into the tank with the pump-fed system, a configuration frequently used on cryogenic vehicles. However, for the LTCSF with screened-channel liquid acquisition devices (LADs) in the propellant storage tanks, operation of such a system in zero gravity would result in liquid bulk boiling in the tank and in the LAD. Significant amounts of vapor formation could restrict liquid flow into the channel and prevent complete transfer. The presence of vapor between transfers could result in screen dryout and ultimate breakdown of the acquisition device. Testing of such a transfer configuration is required in the zero-gravity environment of space to demonstrate its viability for the LTCSF application. For these reasons the pump-fed transfer configuration was eliminated from further consideration in this study.

LTCSF PROPELLANT TRANSFER CONFIGURATIONS

- CONSIDERED PRESSURE-FED, PUMP-ASSISTED, AND PUMP-FED SYSTEMS
- ASSUMED SCREENED-CHANNEL TYPE LIQUID ACQUISITION DEVICE (LAD)
- PUMP-FED CONFIGURATION IN ZERO GRAVITY CAUSES BULK LIQUID FLASHING IN TANK AND IN LAD
- SIGNIFICANT VAPOR FORMATION COULD HAMPER LAD OPERATION AND EVEN RESULT IN SCREEN DRYOUT AND BREAKDOWN BETWEEN TRANSFERS
- ZERO-GRAVITY ORBITAL TEST REQUIRED TO DEMONSTRATE VIABILITY OF PUMP-FED TRANSFER

THEREFORE, PUMP-FED CONFIGURATION ELIMINATED FROM CONSIDERATION

CONSIDERATIONS FOR PRESSURE-FED AND PUMP-ASSISTED TRANSFER

Considerations for comparing the pressure-fed and pump-assisted transfer configurations are shown. Adding a pump to assist in liquid transfer reduces the amount of pressurant, and consequently the amount of energy, which must be injected into the propellant tank. This results in a lower boiloff penalty when the tankage system is returned to its initial thermodynamic condition. Addition of a pump, however, raises significant reliability concerns due to the long life requirement and the large number of thermal and startup cycles the system must withstand. Multiple pumps could make a significant demand on station power during the transfer operation. They must be redundant and be designed to be replaceable on orbit. Also, pump operation is complicated by the requirement to vary propellant flowrate during transfer.

CONSIDERATIONS FOR PRESSURE-FED AND PUMP-ASSISTED TRANSFER

PUMP-ASSISTED

- REQUIRES LOWER TANK PRESSURE, LESS PRESSURANT
- RESULTS IN LESS INJECTED ENERGY, LOWER BOILOFF PENALTY
- MORE COMPLICATED OPERATION TO HANDLE FLOWRATE VARIATIONS
- REQUIRES STATION POWER
- RELIABILITY CONSIDERATIONS INCLUDE LONG LIFE, MULTIPLE CHILLDOWN/ WARMUP CYCLES, MULTIPLE START/STOP CYCLES
- MUST HAVE REDUNDANT, ORBIT REPLACEABLE UNITS
- MAY BE REQUIRED FOR OTV DETANKING

PRESSURE-FED

- REQUIRES HIGHER TANK PRESSURE, MORE PRESSURANT
- RESULTS IN MORE INJECTED ENERGY, HIGHER BOILOFF PENALTY
- NO SUCTION; AVOID FLASHING WITH SLOW-OPENING VALVES
- BACK-PRESSURING REQUIRED TO HANDLE FLOWRATE VARIATIONS

Cryogenic transfer, boost and engine feed line pre-chill pumps which have demonstrated performance and reliability are listed with their specifications. Several are designed to be totally submerged in the pumped fluid. The pumps are powered by either hydrogen peroxide fueled turbines or electric motors. All pumps listed have low NPSP (net positive suction pressure) requirements, which improves pump reliability.

For a propellant transfer operation such as that required for LTCSF, the flow rates are within those which have been previously demonstrated. The most important feature of the pump will be its' ability to be cycled on and off repeatedly over a period of 10 years or more without failure or degradation in performance. For this reason, it is probable that the pumps will be driven by electric motors rather than by hydrogen peroxide turbines.

COMPARISON OF EXISTING PUMP SPECIFICATIONS WITH ON-ORBIT PROPELLANT TRANSFER REQUIREMENTS

Existing Pump Specifications

Application	Liquid	Mass Flow	P_{inlet}	NPSP	Weight	Drive
Centaur	LH_2	11.8 lb_m/sec	20 psia	0.06 psi	62 lb_m	Turbo-peroxide
Centaur	LO_2	61.5 "	30	0.7	53	"
Space Shuttle	LH_2	1.3	14.7	0.03		Motor, 1.02 hp
Saturn IV B	LO_2	4.8	14.7	0.7	14	Motor, 0.8 hp
"	LH_2	1.3	14.7	0.03	15	Motor, 0.8 hp
Fermi Labs	LHe	0.07		0.16		Motor

On-Orbit Propellant Transfer Requirements*

LTCSF LH_2 Transfer	LH_2	1.0	20-25	<1.0	-----	Motor desirable
" LO_2 "	LO_2	5.9	20-25	<1.0	-----	"

* Flowrates are based on transfer of 100,000 lb_m of LO_2/LH_2 in a four-hour period.

LONG TERM CRYOGENIC STORAGE FACILITY
All Passive System Concept with Boiloff Disposal Module

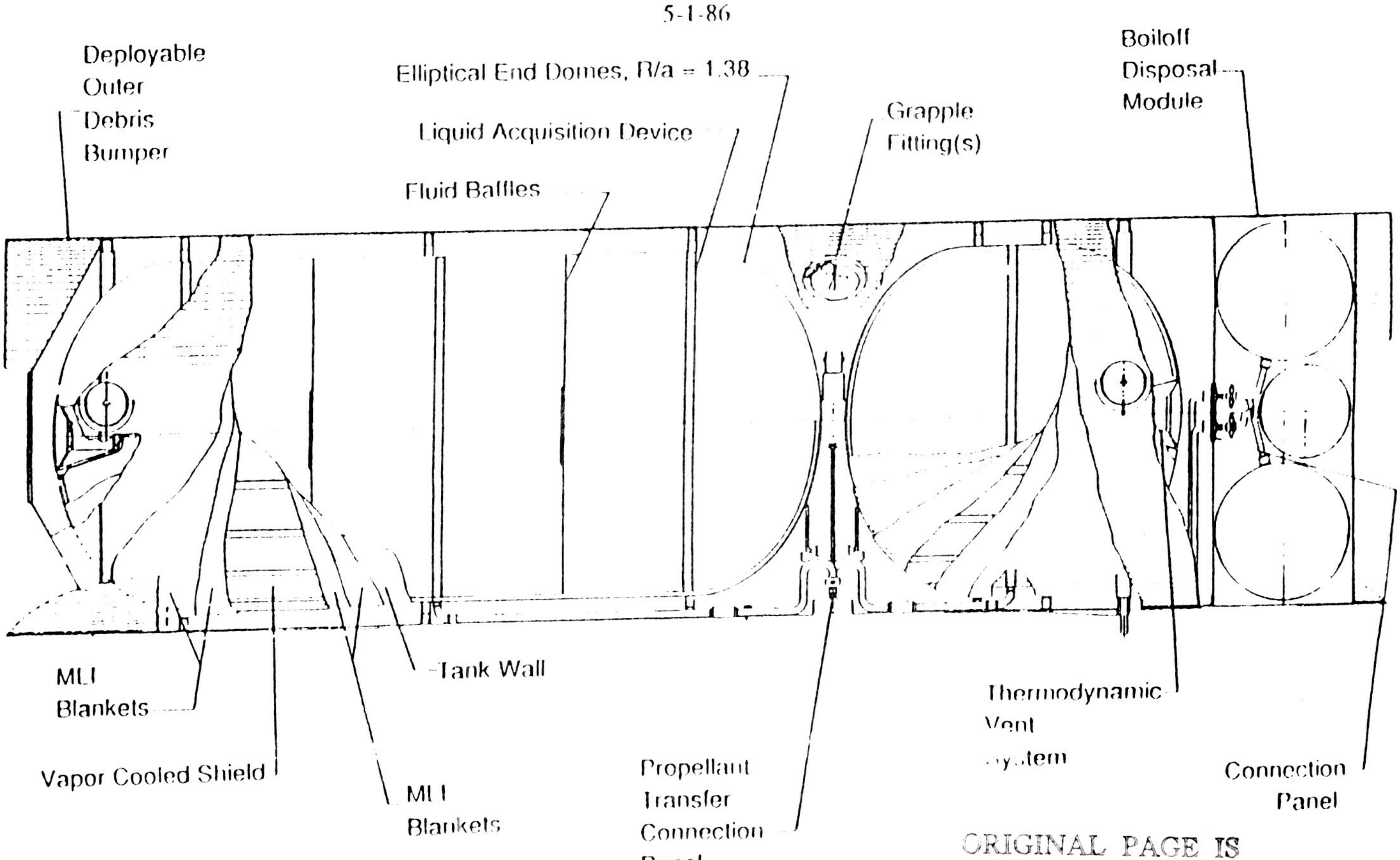
The all-passive storage concept features tandem hydrogen and oxygen tanks contained within a structural shell. The tank set is launched dry and filled on orbit, thus permitting a minimum of structural support through which heat can conduct to cause boiloff.

The tank shells have cylindrical mid-sections with elliptical end domes, both of 154-in. inside diameter, and employ 2219-T87 aluminum alloy. Bulkheads used in these concepts are NASA standard ellipses with a ratio of major radius to minor radius of 1.379. Components located internal to the tank shell include a thermodynamic vent system, mass gauges, the liquid acquisition device and fluid baffles. Tank shells are structurally supported to the inner debris/micrometeoroid shield via a system of glass/epoxy composite struts, and thick multilayer insulation and vapor-cooled shields are used to limit boiloff.

If venting of boiloff is not permitted, such as in the vicinity of the Space Station, the all-passive facility concept includes a single boiloff disposal module affixed at the aft end of one of the tank sets. Four spheres, each five feet in diameter, store gaseous hydrogen boiloff and one 3.5 ft diameter sphere stores the gaseous oxygen boiloff. These vessels are sized to accumulate the 90-day period boiloff plus some contingency for two 100,000 lb capacity tank sets. The other tank set does not have a boiloff disposal module. The boiloff disposal module is periodically detached and transported away from the Space Station by the OMV and is non-propulsively vented to space.

LONG TERM CRYOGENIC STORAGE FACILITY
All Passive System Concept with Boiloff Disposal Module
100,000 lb_m Capacity

5-1-86



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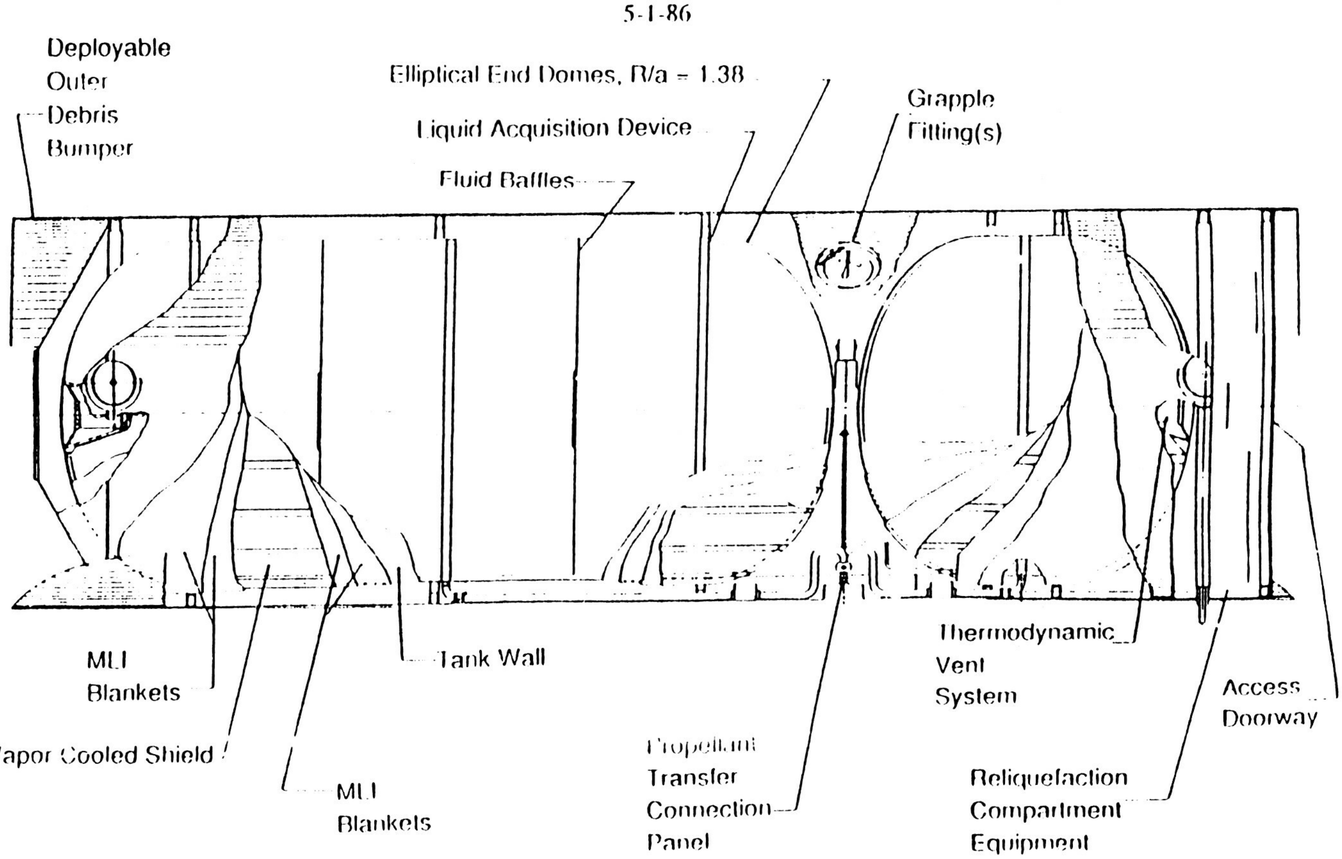
LONG TERM CRYOGENIC STORAGE FACILITY
Total Reliquefaction System Concept

Most of the primary structural elements of the total-reliquefaction system are the same as for the all-passive system. The differences are primarily in the aft bulkhead enclosure where modifications have been made to mount the reliquefaction equipment. Within this compartment are the hydrogen and oxygen pressurant heat exchangers and pumps, the reliquefier and condenser units, and the power conditioning equipment module. All components have been mounted on a graphite epoxy composite isogrid frame to isolate warm side components from cold side cryogenic storage tanks. An access way through the center of the frame is provided since there are doors on the elliptical bulkhead ends of both the hydrogen and oxygen tanks for access to interior on-orbit serviceable and replaceable components, such as the mass gauging instruments, mixers, etc.

A large two-piece door on the aft compartment provides access to the interior equipment modules and serves as the inner component of the two-part micrometeoroid/debris bumper system. Equipment within has been modularized after the design of similar SSP system elements to utilize space servicing tool systems.

LONG TERM CRYOGENIC STORAGE FACILITY
Total Reliquefaction System Concept
100,000 lb_m Capacity
5-1-86

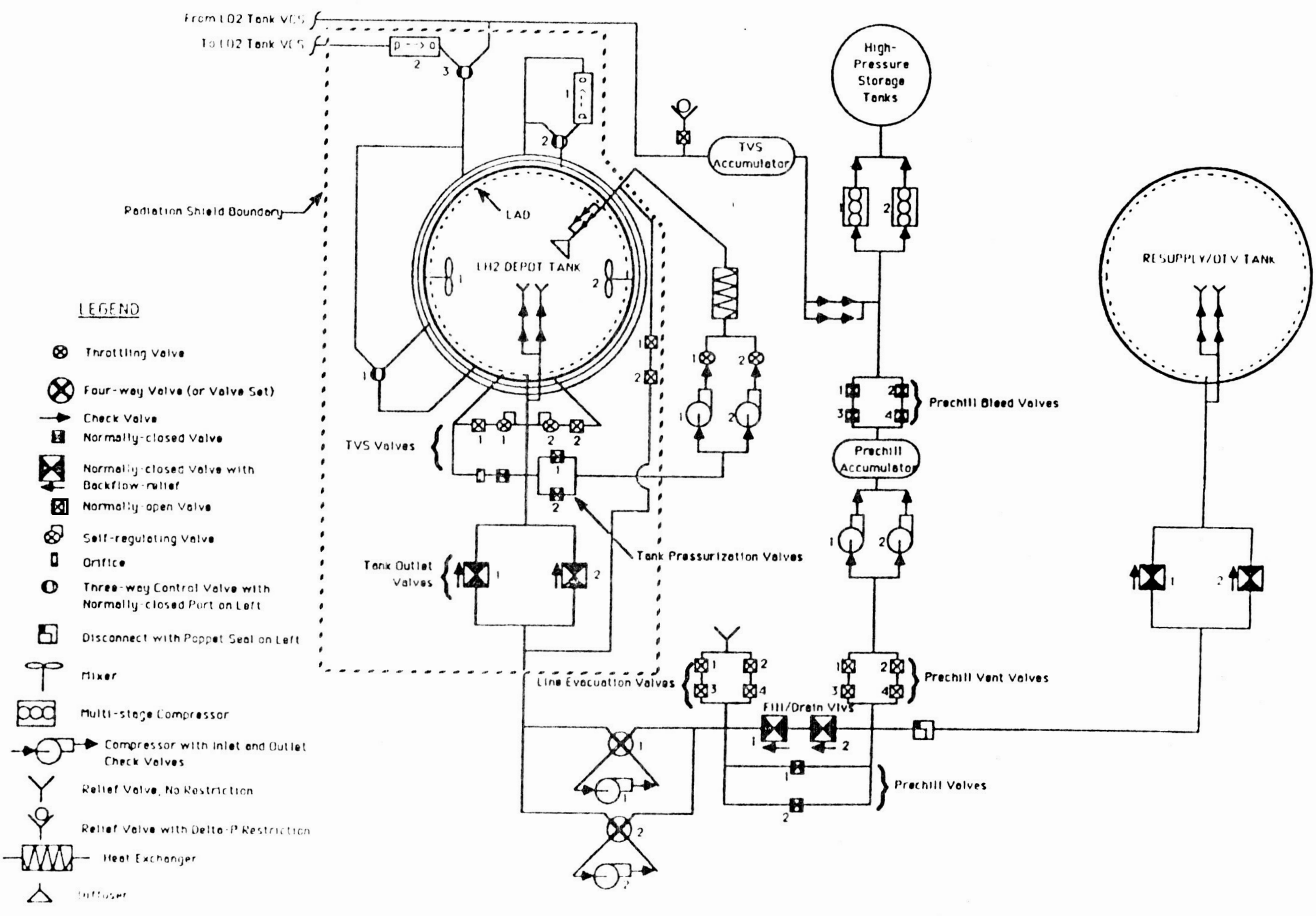


ALL PASSIVE SYSTEM, LH2 FACILITY

This schematic of the hydrogen fluid subsystem for a single tank set illustrates the features necessary to meet functional requirements and the redundancy necessary to provide single failure operational/dual failure safe capability. Steady-state venting from the system can only occur after at least two failures, provided that redundant power supplies are available. Operationally, the system has been designed to perform long-term fluid storage, tank pressurization for fluid transfer, depot tank or OTV tank prechill, and depot tank or OTV tank no-vent fill.

Two important features of the hydrogen system are the line evacuation subsystem and the prechill bleed subsystem. The line evacuation subsystem reduces the pressure of the fluid in the lines that penetrate the MLI/vapor-cooled shield boundary, minimizing the heat input through these lines. The prechill bleed subsystem is used to remove the fluid from the prechill accumulator in a controlled manner in between OTV servicing operations.

ALL PASSIVE SYSTEM, LH2 FACILITY

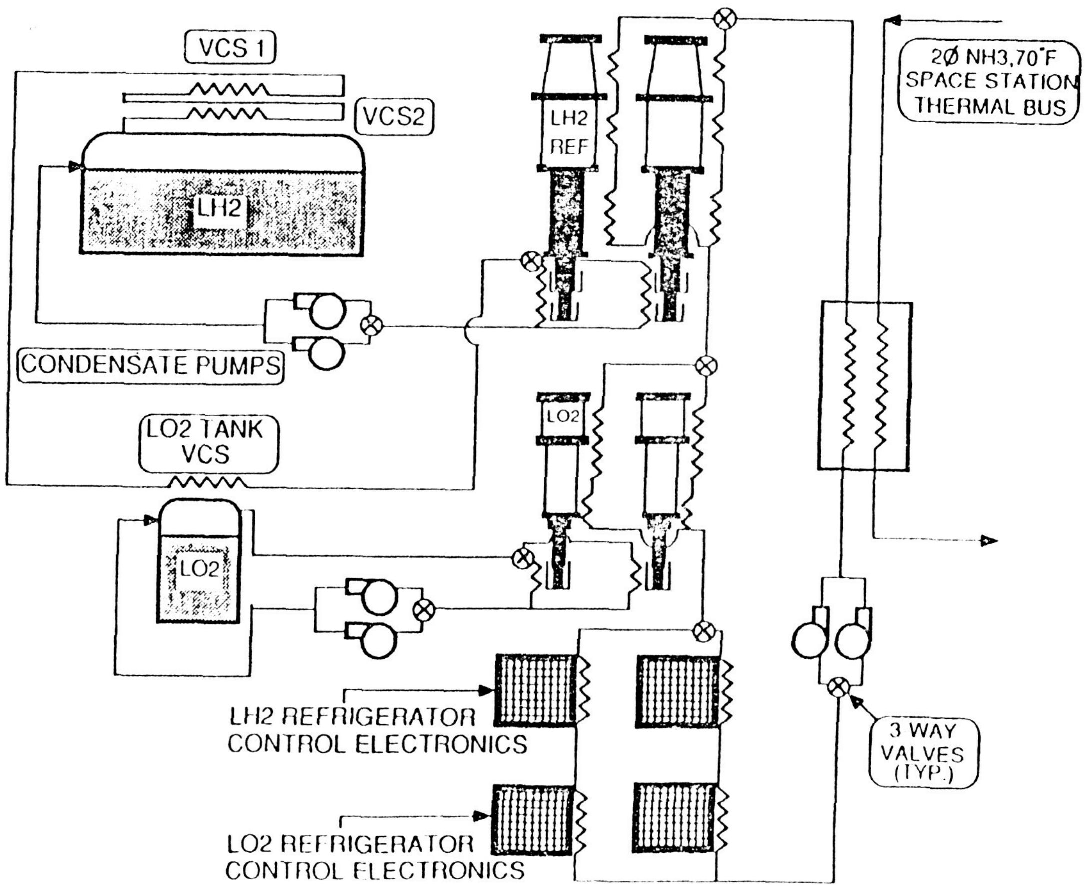


REFRIGERATION SYSTEM

The refrigeration subsystem required for reliquefaction of boiloff uses separate hydrogen and oxygen refrigerators in order to provide the best thermodynamic performance and to permit separate control over the hydrogen and oxygen streams.

The oxygen refrigerators are single-stage devices that provide cooling for both desuperheating and condensing the oxygen boiloff. The hydrogen refrigerators are two-stage devices that provide desuperheating on the first stage and condensing on the second stage. The refrigerators are magnetic suspension, free piston, Stirling machines that are hermetically sealed and use gaseous helium as the refrigerant. Condensate pumps return the condensed liquid to the storage tanks, and circulation pumps provide cooling for both the refrigerators and their control electronics. The refrigerators are heat sinked to the Space Station thermal bus.

REFRIGERATION SYSTEM

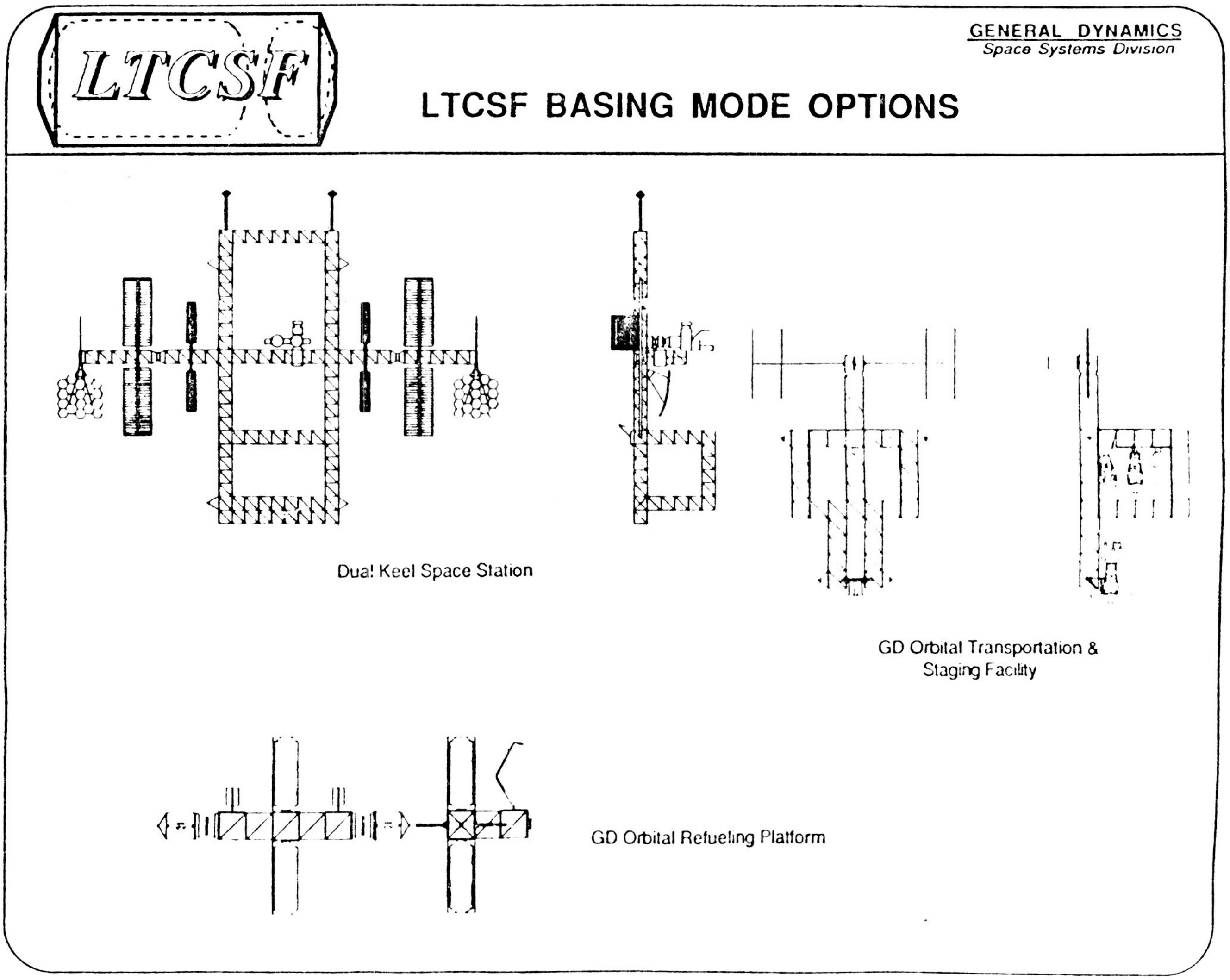


LTCSF BASING MODE OPTIONS

Three different types of basing platforms for the LTCSF were identified, they are:

- the Dual Keel Space Station Platform (SSP)
- an Orbital Transportation and Staging Facility (OTSF)
- an Orbital Refueling Platform (ORP)

The LTCSF is needed to supply propellant to the Orbital Transfer Vehicle (OTV), in order to accomplish this the LTCSF could be placed on a manned platform (SSP) with the OTV. Another option would be to place the LTCSF on an unmanned platform (OTSF) with the OTV and its servicing facility, this platform could co-orbit with the SSP or be in a polar orbit. The last option places the LTCSF on a separate dedicated orbital refueling platform.



LTCSF/BASING MODE COMPATIBILITY

The all-passive LTCSF is compatible with all the basing concepts except the SSP, because venting of the boiloff could contaminate station surfaces or create disturbances detrimental to experiments on the station. However, these problems could be overcome by tethering the LTCSF off of the station. The passive LTCSF with a boiloff disposal module or total reliquefaction could be used on the SSP since no venting of propellants is required. The passive LTCSF with BDM or total reliquefaction could be used on the OTSF or ORP but the power and disposal requirements are not justified by the small amount of propellant saved. Additionally venting on these platforms is not considered a problem.

GENERAL DYNAMICS
Space Systems Division

LTCSF/BASING MODE COMPATIBILITY MATRIX

		BASING MODE			
		SPACE STATION		ORBITAL TRANSP. & STAGING FACILITY	ORBITAL REFUELING PLATFORM
		HARD DOCKED	TETHERED		
LTCSF OPTIONS	1. ALL PASSIVE	NO VENTING ALLOWED	✓ VENTING OF BOILOFF ALLOWED	✓ VENTING OF BOILOFF ALLOWED	✓ VENTING OF BOILOFF ALLOWED
	2. ALL PASSIVE WITH BOILOFF DISPOSAL MODULE	✓ DISPOSE OF BOILOFF IN CARRY-AWAY STORAGE VESSELS			
	3. TOTAL RELIQUEFACTION	✓ NO DISPOSAL OR VENTING REQD.			

✓ INDICATES RECOMMENDED OPTIONS

TEST PROGRAM

The objective of the test program is to reduce the technical risk associated with fielding an orbital propellant depot. A methodical approach to test program definition was taken by identifying technical risks to the component level, analyzing test article size considerations and defining six test options. The options were evaluated based on the risk reduction they provide, their compatibility with the overall development schedules for the full scale orbital storage facility, the Space Station and the OTV, and test option cost. The option recommended involves subscale integrated system testing both on the ground and on orbit.

Orbital testing could be either a short-term test carried out in the cargo bay of the Space Shuttle Orbiter using a non-hazardous cryogen or a longer-term test carried out with hydrogen aboard a free-flying experiment orbited with an expendable launch vehicle. Extended ground tests would be conducted with active components, and liquid acquisition device degradation in liquid oxygen would be investigated. For the cargo bay option MLI, solar coatings and micrometeoroid/debris shield materials would be given extended orbital exposure with a LDEF-type experiment.

The duplicate qualification hardware and extensive integration effort for the cargo bay experiment may be equivalent in cost to the extra systems required for the free-flier.

OBJECTIVE

- **Reduce The Technical Risk Associated With Fielding An Orbital Propellant Depot**
  - Operating life of active components
  - Zero-g fluid management technology
  - Thermal performance
  - Integrated system performance
  - Degradation of materials on orbit

APPROACH

- Identify techical risks down to component level
- Determine scale of test articles
- Define testing options
- Evaluate options based on resulting risk reduction, schedule compatibility, and cost

CONCLUSIONS / RECOMMENDATIONS

- Both ground and orbital testing
- Orbital systems test with hydrogen free flier or alternate cryogen in Orbiter cargo bay
- Shuttle qualification requires extra hardware
- Shuttle integration is an extensive engineering task

LTCSF FLIGHT EXPERIMENT

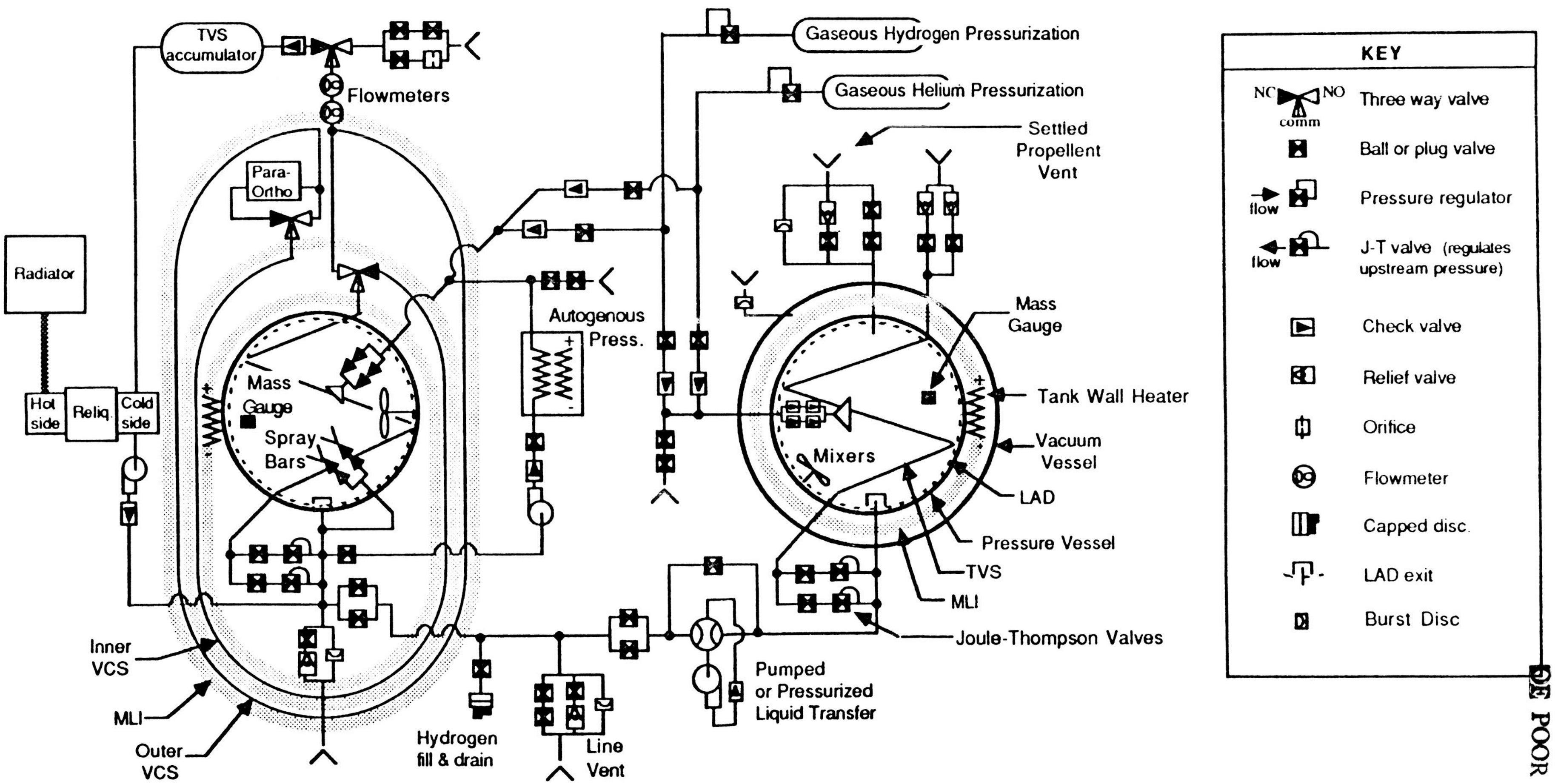
The subscale, free-flying experiment is intended to investigate both zero-g fluid management and transfer and long-term cryogenic storage. At launch the experiment is contained within a Contraves 4 meter diameter fairing, and the solar panels and antennae are folded for packaging.

The experiment uses a cylindrical receiver tank for carrying out hydrogen transfer tests and a spherical dewar tank for storage of the hydrogen on the ground and during launch. A hydrogen boiloff reliquefier is included along with features for autogenous and stored gas pressurization. A micrometeoroid/debris shield surrounds the experiment, and an external, heat pipe radiator is used to reject reliquefier and avionics waste heat.

EXPENDABLE VEHICLE EXPERIMENT FLUID SYSTEMS

Experiment fluid systems will be designed to be fail operational to an extent which insures successful accomplishment of the experiment objectives. The experiment features reliquefaction, autogenous pressurization, stored helium or hydrogen pressurization, pumped or pressurized liquid transfer, thermodynamic venting, vapor-cooled shields, para to ortho conversion, and zero-g mass gauging. All tanks and lines in which liquid could be trapped are protected by relief valves and burst discs to insure experiment success and prevent the generation of debris from a ruptured vessel.

EXPENDABLE VEHICLE EXPERIMENT FLUID SYSTEMS



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EFFECT OF TANK SIZE ON EXPERIMENT MASS

The scale of the baseline experiment was selected to have the same size tanks as the Orbiter cargo bay experiment. For an expendable vehicle-launched experiment the scale can be selected to take advantage of a particular booster's capability.

The following assumptions were used to develop the scale curve shown.

The mass of hydrogen, meteoroid/debris shield, and high pressure gas bottles are proportional to the volume of the receiver tank.

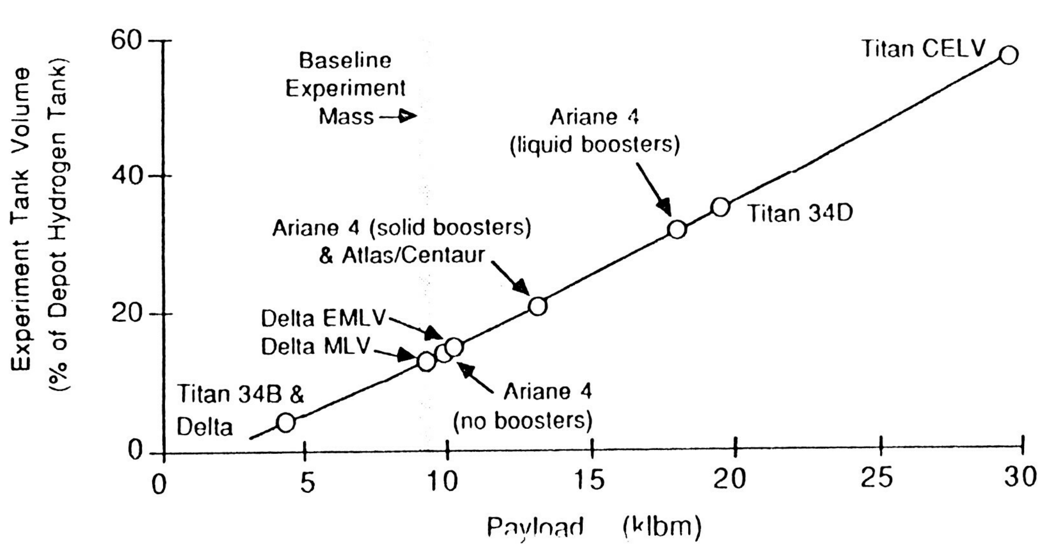
The mass of the receiver tank, dewar tank, solar cover, support structure, and accumulator are proportional to the surface area of the receiver tank. [or the $(\text{volume})^{2/3}$]

The mass of the plumbing, valves, and para-ortho converter are proportional to the diameter of the receiver tank. [or the $(\text{volume})^{1/3}$]

The mass of the pressurization system, reliquefier, radiator, solar arrays, batteries, deployment mechanisms, and avionics are independent of the experiment scale.

The ACS system is assumed to be 10% of the mass of everything else combined.

EFFECT OF TANK SIZE ON EXPERIMENT MASS



CRYOTANK SYSTEM LEVEL DEVELOPMENT TESTING PROGRAM

General Dynamics Space Systems Division is conducting an IR&D testing program to explore technologies for long term storage of cryogens in space. The first phase of the program involves the development of a hydrogen test assembly and operation of the assembly in both passive and active boiloff management modes. The assembly consists of cryogen tank and vacuum chamber with various boiloff management features. Component testing objectives include:

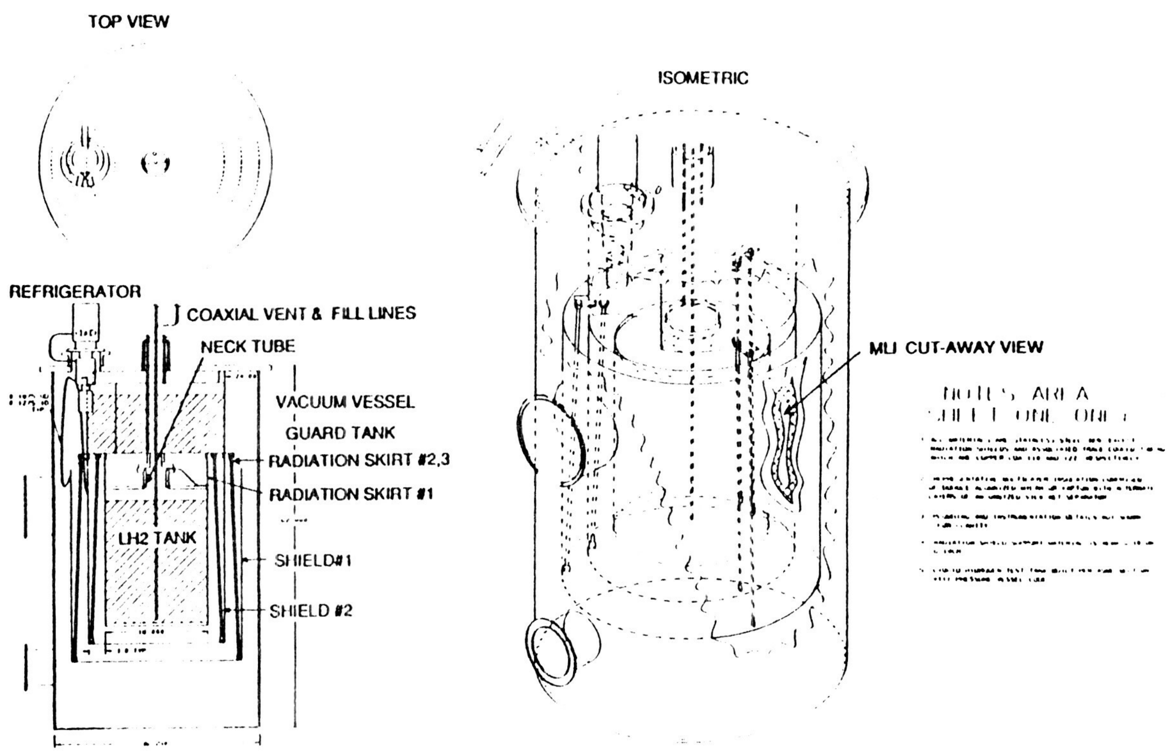
1) Single and dual vapor-cooled shield design optimization;
2) Para-ortho hydrogen converter performance;
3) Multilayer thermal radiation insulation blanket performance;
4) Closed-cycle cryogenic refrigeration to cool radiation shields to adjust hydrogen tank condition/boiloff rate.

System-level issues being addressed include:

1) Design/control of vapor-cooled shields to achieve optimum performance;
2) Integration of all components to preserve performance;
3) External control of passive/active boiloff management without disassembly of system;
4) Maintainability/reliability.

Air Products and Chemicals, Inc. is participating in the R&D program by providing the refrigerator, the para-ortho converter and consultation on hardware integration.

CRYOTANK SYSTEM LEVEL DEVELOPMENT TESTING PROGRAM



LH2 TEST TANK STAINLESS STEEL

SPEAKER: JOHN R. SCHUSTER/GENERAL DYNAMICS SPACE SYSTEMS

Hugh Arif/Analex Corporation--Lewis Research Center:

I have a question, actually three questions, regarding the debris shield. Did you consider using the vapor cooled shield as the debris or the micrometeorite protection shield?

Schuster:

Yes, we've given some consideration to that. The vapor cooled shields are imbedded part way into the multilayer insulation system. In addition to that, the vapor cooled shields do have cooling tubes on them. In order to utilize those as part of the debris protection, you would have to assume that there would be particles that would penetrate at least a portion of the MLI and possibly strike some of the cooling tubes on the vapor cooled shield. Such an occurrence would possibly create a leak in your system, and then everything would be over. We concluded that the best approach is to design the protection system based on the assumption that you contain all the particles within that protection system and nothing gets inboard this system to the MLI or the vapor cooled shield.

Arif:

My second question concerns one of your configurations. You showed a separate shield for the debris protection and a separate one for the micrometeorite protection. What was the reason for that?

Schuster:

That is just the way the sketch was labeled. It really is a system that works together; the outer shield fragments particles, whether they are micrometeroites or debris, and it is a relatively thin shield. It is maybe only 25 percent as thick as the inner shield. The inner shield stops the fragmented particles, and it is also thick enough to provide structural support for suspending the tanks inside that configuration.

Arif:

Thirdly, as part of your test program, do you actually conduct proof tests on what thickness of debris shield you should have to withstand the different sizes of particles?

Schuster:

We recommended that be one of the development areas where some engineering data be taken. We would recommend that they look at a range of materials, as well as a range of impact conditions, such as the angle of incidence, velocity, and particle diameter, so that you collect engineering data over the range of parameters that show up in the penetration models.

Steve Colaprete/Ball Aerospace:

John, you said that the preferred approach was the passive insulation system on the storage system. What kind of thermal performance did you consider to be acceptable for that system, say in percent per year boil off?

Schuster:

Well, it depends on the condition of the solar-selective coating on the outside of the system. For a normally degraded coating with Alpha over Epsilon of 0.4, which is quite degraded, we would have a boil-off rate on the order of 0.2 to 0.3 of a percent per month, based on combined hydrogen and oxygen boil off.

Calvin Wilkinson/Boeing Aerospace:

I couldn't read the dimensions on the last chart you had.

Schuster:

The tank is about 18-inches in diameter